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RESEARCH ON DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR BASED ON NEW STATOR FLUX LINKAGE SETTING

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Abstract:-
Aiming at the torque ripple problem of Brushless DC motor, a new stator flux setting method is proposed on the basis of direct torque control system. Firstly, the basic forming principle of traditional stator flux vector locus of circular and hexagonal is analyzed.And then, a new stator flux linkage setting method based on rotor position and dynamic current mode is proposed.The new stator flux linkage method is applied to the direct torque control system of Brushless DC motor.Theoretical analysis shows that the given flux linkage trajectory is consistent with the expected reference value, the torque ripple is smaller. The simulation results verify its effectiveness and are suitable for BLDCM DTC operation.

Keywords:- *Brushless DC motor; direct torque; dynamic current setting; stator flux given; vector trajectory*

INTRODUCTION

Permanent magnet brushless DC motor has been widely used in industrial control and production, life, medical devices and other fields because of its simple structure, high efficiency, easy maintenance and other advantages[1]. However, the brushless DC motor controlled by PWM can not only cause the electromagnetic torque to be more pulsating, and the torque ripple caused by non ideal back EMF can not be effectively suppressed, which greatly limits its application in high precision systems[2]. To solve this problem, the brushless DC motor direct torque control method with simple control structure, fast torque response and strong parameter robustness has been applied to more and more DC motor control systems by more and more scholars[3].

Direct torque control gives up the idea of decoupling in vector control. In order to improve the performance of torque dynamic response, the instantaneous power angle is adjusted in time by adjusting the stator flux size and moving speed in the established space vector, and finally the direct torque control is achieved[4]. Therefore, it is not difficult to find that the given stator flux linkage is the basis of direct torque control. However, few studies have been done on the given stator flux linkage in the study of direct torque control of Brushless DC motor. In the brushless DC motor, Because of the complicated reasons such as the particularity of the air gap magnetic field, and the uncertainty of off phase voltage and so on, the running track of stator flux is not a simple circular or hexagonal to outline. Therefore, the direct torque control of Brushless DC motor can not simply apply the given experience of given stator flux in the direct torque control[5].This paper compares and analyzes the setting method of traditional hexagon and circular stator flux linkage locus. The new method of setting the given stator flux linkage is introduced into the direct torque control of Brushless DC motor. The effectiveness of the proposed method is verified by experimental simulation.

1 Analysis of the traditional given method of stator flux

1.1 given method of hexagon track flux

The design of hexagon stator flux linkage track is mainly used in high power and low switching frequency drive system, such as megawatt class motor drive locomotive, the voltage and linkage space vector diagram is shown in figure 1.

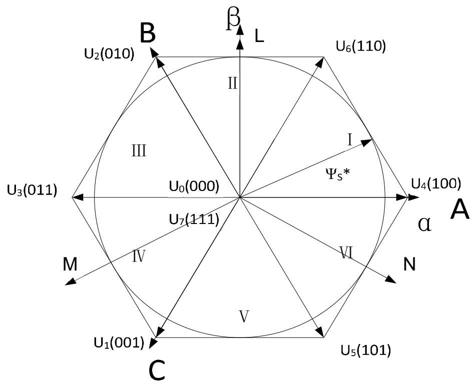

Fig.1 voltage space vector of hexagon stator flux linkage trajectory

When the stator flux is running along the trajectory of the hexagon as shown in the figure 1 above, the switch of the inverter needs to be switched once when stator flux is running to each corner of the hexagon. As a result, it only takes the inverter six times to switch in one electric period of stator flux linkage motion. Each switch only needs to turn off a power tube and open another [6].

The value of given magnetic flux is defined as ψs^*, as can be seen from Fig.1, the magnitude of the stator flux linkage is not a constant, so the ψs^* will not be constant. In order to reduce the difficulty in controlling, the radius of inscribed circle of hexagon flux linkage locus is set as the given flux linkage ψs^*, which is convenient for the comparison of the flux latter, and reduce the complexity of the hexagon flux linkage trajectory. Thus, in the design of conventional hexagonal flux linkage trajectories, the most important step is to specify the ψs^* as a constant value.

As shown in Fig.1, the LMN coordinate system is rotated ninety degrees counterclockwise by the ABC coordinate system. The stator flux linkage is ψ_L、ψ_M、ψ_N in the three axes of the LMN coordinate system, compare them with the given stator flux linkage ψs^* seperately. The output of the hysteresis regulator determines the selection of the voltage vector, which finally realizes the control of the actual motion direction of the stator flux linkage, and complexity of the control can be greatly reduced.

The component of the stator flux linkage on the LMN axis can be transformed from the component on the αβ axis. The transformation between αβ coordinate system and LMN coordinate system is:

$$\begin{cases} \psi_L = \psi_\beta \\ \psi_M = -\dfrac{\sqrt{3}}{2}\psi_\alpha - \dfrac{1}{2}\psi_\beta \\ \psi_N = \dfrac{\sqrt{3}}{2}\psi_\alpha - \dfrac{1}{2}\psi_\beta \end{cases} \qquad (1)$$

The stator flux linkage in the αβ coordinate system is calculated by the component of the space voltage and current vector on the αβ axis:

$$\begin{cases} \psi_\alpha = \int (u_\alpha - i_\alpha R) dt \\ \psi_\beta = \int (u_\beta - i_\beta R) dt \end{cases} \qquad (2)$$

Compare the ψ_L、ψ_M、ψ_N with the given flux value ψs^* through the comparator. When the stator flux increases to $+\psi s^*$, the comparator output 1, when the stator flux decreases to $-\psi s^*$, the comparator output 0. The input - output relation is:

$$S_{\psi_{L/M/N}} = \begin{cases} 1 & (\psi_{L/M/N} \geq \psi_S^*) \\ 0 & (\psi_{L/M/N} \leq -\psi_S^*) \end{cases} \qquad (3)$$

The voltage space vector corresponding to different sectors can be obtained:

$$V_X = (S_{\psi_M} \quad S_{\psi_N} \quad S_{\psi_L}) \qquad (4)$$

In the formula (4), $S_{\square M}$、$S_{\square N}$、$S_{\square L}$ respectively represents the output value after comparing ψ_L、ψ_M、ψ_N with the given value of magnetic flux ψs^*.Therefore, the output voltage space vector can be controlled by three magnetic flux comparators, and the 6 working states of the inverter can be simply switched to realize the tracking control of the magnetic flux linkage.

Compared with other methods, this control method is simple in structure and small in switching frequency, but it also causes large current harmonics. The torque ripple cannot be well controlled, and the noise is obvious.

1.2 Given method of circular track flux

The basic idea of traditional circular flux linkage trajectory control is to control the deviation of the flux linkage trajectory in a certain range [7].Fig.2 shows a circular stator flux linkage tracking method. It is different from the interval division method of stator flux linkage track of hexagon. The stator flux linkage trajectory is divided into six regions according to the direction of u1、u2、u3、u4、u5、u6 in the form of circular stator flux linkage tracking.

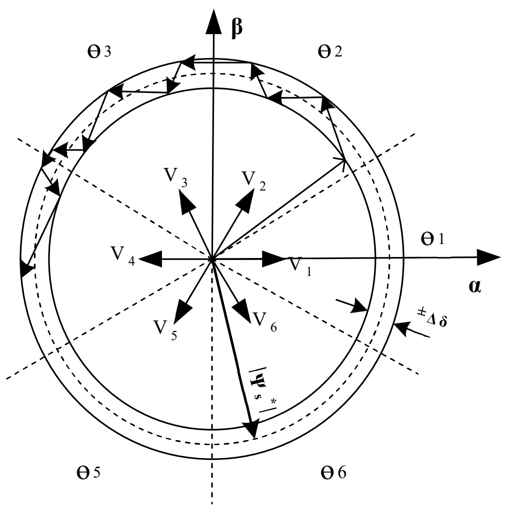

Fig.2 voltage space vector diagram of circular stator flux linkage locus

The stator flux ΨS can be regarded as the superposition of the stator and rotor flux linkage:

$$\psi_s = L_s i_s + \psi_f e^{j\theta} \qquad (5)$$

In the formula (5), □*f* represents the rotor induced flux, L_s represents the stator inductance, and the i_s represents the stator current. And motor back emf can be expressed as:

$$e = \frac{d\psi_f}{dt} = \frac{d\left(\left|\psi_f\right|\cos\theta\right)}{dt} = \frac{d\left(\left|\psi_f\right|\cos\left(\omega t+\theta_0\right)\right)}{dt} = \left|\psi_f\right|\omega\cdot\sin\left(\omega t+\theta_0\right) \qquad (6)$$

In the formula(6), □ represents the rotor mechanical angular speed, and □0 represents the rotor's initial position angle. Since $L\, i_{s\,s}$ can be neglected, and $e^{j□}$ □1 , we can get the following relation combining the formula(5) and formula(6):

$$\left|\psi_s\right| = \left|\psi_f\right| = \frac{e}{\omega} \qquad (7)$$

We can get from the formula $U = Ri + L\frac{di}{dt} + e$

that:

$$U \approx e \qquad (8)$$

The amplitude of the given stator flux $\left|\psi_s^*\right|$ is:

$$\left|\psi_s^*\right| = \frac{U}{\omega} = \frac{U}{2\pi f} \qquad (9)$$

In the formula(9), *U* is the peak of phase *n*□P

$$\psi_s(t) = \int_0^t \left(u_s - Ri_s\right)d\tau + \psi_0 \qquad (10)$$

In the formula above, □0 is the initial value of the flux linkage. The influence of stator resistance pressure drop can be neglected under the condition that the frequency of the motor is not very low. In the period of □*t* when space vector u_s acts from t_1 to t_2 , the upper formula can be discretized into:

$$\Delta\psi_s = \psi_s(t_2) - \psi_s(t_1) \approx u_s \Delta t \qquad (11)$$

From the formula (11), it can be seen that the choice of the space vector not only determines the speed of the stator flux linkage, but also determines the direction of it. According to fig.2, in order to guarantee the circular motion trajectory of the stator flux linkage, the magnitude of the stator flux $□_s^*$ should be controlled within the minimum deviation of the given stator flux linkage:

$$\left|\psi_s^*\right| - \Delta\delta \le \left|\psi_s\right| \le \left|\psi_s^*\right| + \Delta\delta \qquad (12)$$

In the formula(12), □□represents the deviation range allowed by the flux. The amplitude of the actual stator flux is approximated to a constant value when the voltage vectors are switched in time. The choice of the voltage space is determined by the value of the actual flux linkage and the sectors in which it is located. According to fig.2, assuming the actual flux is located in the□3 sector and is contrarotating, if the flux amplitude is too large, then select V5 to reduce it. On the other hand, if the flux amplitude is too small, select V4 to maintain the actual flux linkage amplitude stability. Although the setting method of given flux linkage can suppress the torque ripple better, the performance of dynamic response is also improved, but it can not be applied to the brushless DC motor with complex air gap field.

2 New setting method of given stator flux linkage

The complicated air gap magnetic field causes the stator flux linkage trajectory to become more complicated[8]. Therefore, the original magnetic flux given way can not be simply applied to the control of brushless DC motor. Considering the dynamic response performance of the control system, a new design method of given stator flux linkage based on rotor position and reference current function is proposed in this paper.

In the three-phase inverter circuit, according to the six switching states of the power switch tube, the corresponding six non zero voltage vectors of V1 to V6 are obtained, and the division of the voltage space vector is shown in Fig.3.

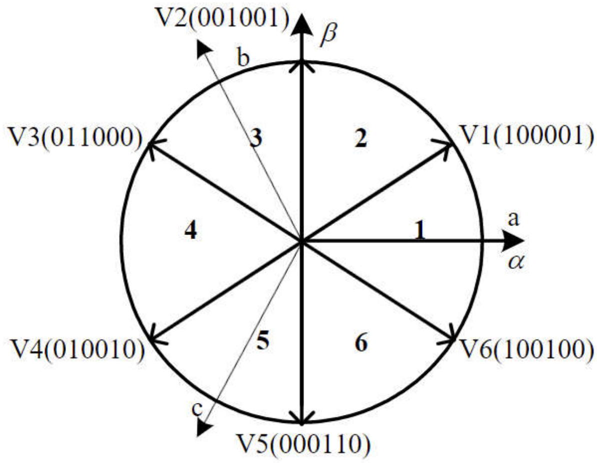

Fig.3 voltage space vector diagram of BLDCM

Ignoring the influence of the leakage flux, the stator flux is the vector sum of the rotor induction flux and the armature reaction flux:

$$\psi_s = L_s i_s + \psi_f e^{j\theta} \qquad (5)$$

In the formula (13), $_f$ is produced by the excitation of rotor permanent magnet, and related to the rotor position. □$_a$ is caused by stator current. How to select suitable stator current setpoint is the key to set the given stator flux linkage of BLDCM DTC.

2.1 Given rotor flux linkage

As shown in Fig.4, the waveform of the three-phase EMF of the brushless DC motor is trapezoidal. The induction flux value of rotor of Brushless DC motor is the integral function of the corresponding stator back EMF.So at the top of the trapezoidal wave, the integral of back EMF is a straight line. That is to say, the rotor flux in the flat top stage is linear with the time. When the back EMF is in the ramp stage, the integral curve of the back EMF of the rotor is the quadratic curve. Fig. 4 shows the diagram of the three-phase rotor flux to the time.

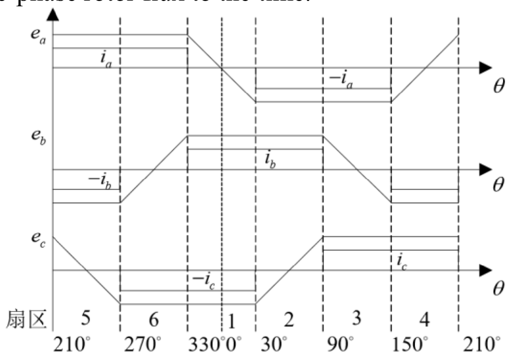

Fig.4 three-phase back EMF

In the stationary coordinate system of α and β, the vector trajectory of the rotor flux is approximately circular, as shown in fig.5.

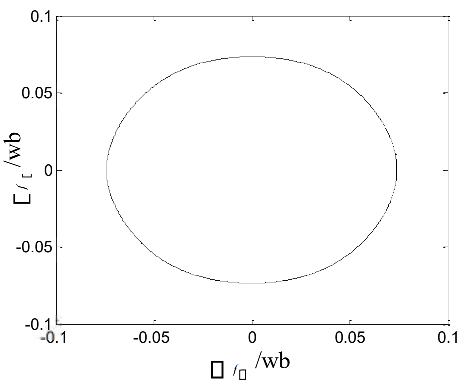

Fig.5 vector trajectory of rotor induction flux

2.2 Given armature response flux linkage

As can be seen from Fig.4, the stator current value is related to the position of the rotor at different moments, and it can be seen from the formula (14) that the stator current determines the stator flux linkage.

In the direct torque control of Brushless DC motor, the given value of the electromagnetic torque T_{ref} is linear with the given current value I_{ref}:

$$\psi_a = Li \qquad (14)$$

$$I_{ref} = T_{ref} / k_e \qquad (15)$$

In Formula(15), ke represents the torque constant. In order to improve the dynamic response performance of the system, the given current value can be dynamically changed according to the motor running state. In combination with figure 4, a dynamic three-phase current setting scheme as shown in Table 1 is given.

Tab.1 dynamic current setting table

Rotor angel	210-270	270-330	330-0 0-30	30-90	90-150	150-210
i_{aref}	i_{ref}	i_{ref}	0	$-i_{ref}$	$-i_{ref}$	0
i_{bref}	$-i_{ref}$	0	i_{ref}	i_{ref}	0	$-i_{ref}$
i_{cref}	0	$-i_{ref}$	$-i_{ref}$	0	i_{ref}	i_{ref}

When the motor is in steady operation, as the given value of the current in each phase is given according to the current sector of the rotor, a constant pulsation free electromagnetic torque will be obtained under the ideal back emf.Because of the linear relationship between I_{ref} and T_{ref}, the change of load torque can be seen intuitively combining with the given current in the dynamic ammeter. Therefore, this current setting scheme is suitable for the motor operation under various load conditions. Combining formula (14), the given value of reaction flux of three-phase armature can be obtained. Finally, in the two phase stationary coordinate system, a composite armature response flux linkage vector is synthesized, and the flux linkage trajectory is shown in figure 6.

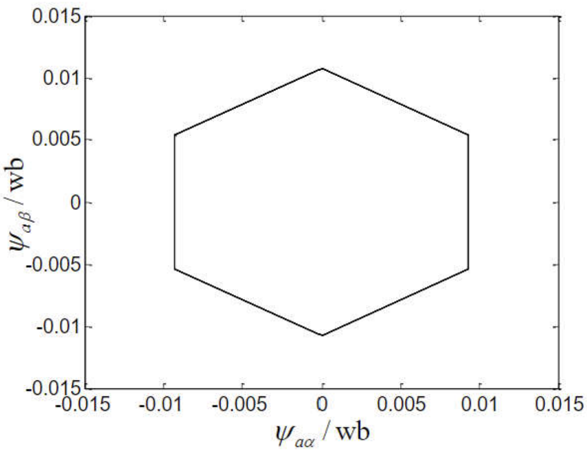

Fig.6 vector locus of armature reaction flux linkage

2.3 given stator full flux linkage The rotor induction flux vector and armature response flux linkage vector are synthesized in a two phase stationary coordinate system, and the function of given stator flux linkage □$_s$ of BLDCM DTC is obtained:

$$\begin{cases} \psi_{S\alpha} = \psi_{f\alpha} + \psi_{a\alpha} \\ \psi_{S\beta} = \psi_{f\beta} + \psi_{a\beta} \end{cases} \qquad (16)$$

respectively. □a□、□a□represents the the rotor flux linkage on the □、□ axis respectively. □$_f$ and □$_a$ are both functions of rotor position, so □$_s$ is also a function of rotor position. When the rotor is in different positions, the given flux linkage is different. The synthesis trajectory is shown in Figure 7.

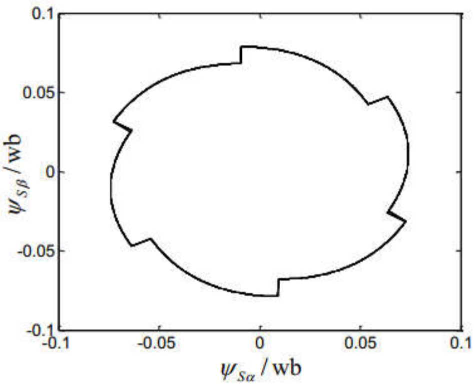

Fig.7 stator flux linkage locus

3 BLDC-DTC based on the new stator flux linkage mode

The basic control principle of direct torque of Brushless DC motor is shown in figure 8. In DTC, the size and direction of the flux are controlled by switching the different voltage space vectors, by controlling the stator flux linkage and stopping at different time periods, the flux angleθcan be changed in time, and the direct control of motor torque can be finally realized[9-10].

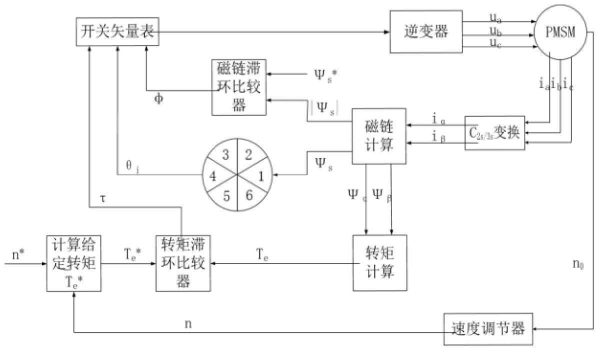

Fig.8 schematic diagram of BLDC-DTC

The measured voltage and current in the three-phase stationary coordinate system are converted to the values in the two phase stationary coordinate system via the Clarke transform. Then the stator flux is calculated according to formula (2), and the sector of the flux linkage is determined. At the same time, the value of the caculated stator flux is compared with the value of the given stator flux linkage.

When □$_s{}^*$□□$_s$ □0 , the output comparison value. The electromagnetic torque T_e can be calculated according to formula

$$T_e = \frac{3}{2} n_p \left(\psi_\alpha i_\beta - \psi_\beta i_\alpha \right) \qquad (17)$$

Compare the value of T_e to the given torque, and output the comparison result ΔT、$\Delta\Psi$ Suppose that the allowable deviation between given torque T_e^* and actual torque Te is . When， the output comparison value T is 1， which controls the switch of six nonzero voltage space vectors, and the stator flux continues to operate to increase the flux angle, which finally increases T_e. When T_e the output comparison value T is 0， the voltage vector is switched to zero voltage space vector, the stator flux linkage is stopped, thereby reducing the magnetic flux angle and reducing T_e. Through T、and the sector value, the corresponding voltage space vector can be selected, so that the direct control of the flux linkage and torque of Brushless DC motor can be achieved.

4 Simulation result analysis

The system model is established and simulated in MATLAB, and the motor parameters are set as：rated voltage U=160V ， rotary inertia $J = 2.1405e-4N\cdot m^2$, stator resistance Rs □ 0.086□ , stator inductance $Ls = 1.12e-3H$ ， mutual inductance $Lm = 0.37e-3H$ ， number of pole-pairs P =3. Fig. 9 (a) shows the stator flux linkage trajectory of the given stator flux linkage. Fig. 9 (b) is the simulation result of the actual stator flux linkage. It can be seen that the actual stator flux linkage can effectively track the given trajectory.

Fig. 10 shows the waveform of the electromagnetic torque in steady state. When the load torque varies from 0 to 1.0N m , it can be seen that the dynamic response time of the torque is very short（about 1.5ms ）， which keeps the advantages of fast torque response inherent in direct torque control, and has little overshoot and no static error in steady state.

Fig. 11 shows the motor speed waveform at a given speed of 50rad/s. When the load changes from zero to 1N.m at the time of 0.05s, the speed has a certain overshoot, but soon stabilizes, which shows that the response time of the system is short in the new stator flux linkage given method. Moreover, when the load torque changes, the speed fluctuation is smaller, which shows that the new stator flux setting method is more suitable for BLDCM DTC operation.

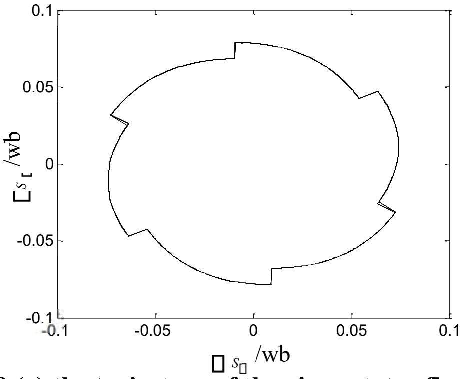

Fig.9 (a) the trajectory of the given stator flux linkage

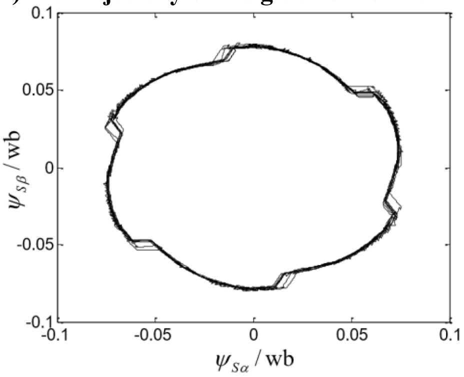

Fig.9 (b) the trajectory of the actual stator flux linkage

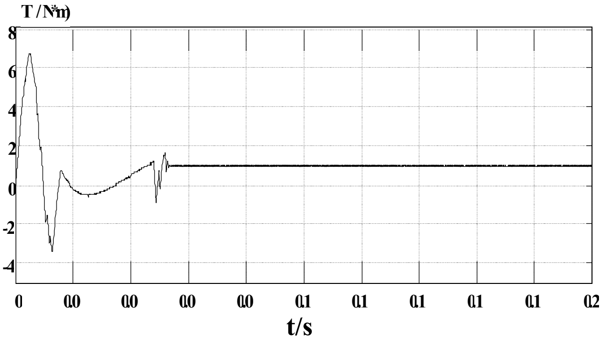

Fig.10 torque waveform of the new magnetic flux setting method

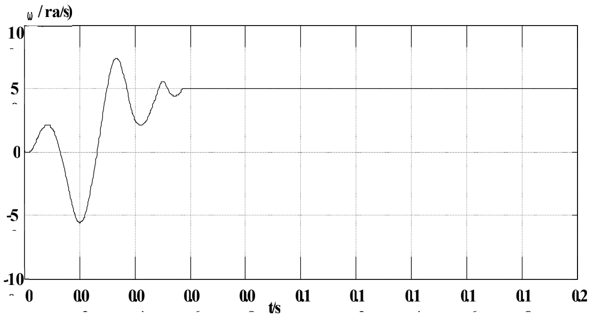

Fig.11 speed waveform of the new magnetic flux setting method

5 **CONCLUSIONS**

The traditional stator flux linkage setting method of DTC is analyzed in this paper, the torque ripple of hexagon flux linkage is larger, and the given method of traditional circular flux linkage can not be applied to brushless DC motor. Therefore, a new stator flux linkage setting method based on rotor position function and dynamic current setting method is proposed and applied to direct torque control of Brushless DC motor.Theoretical analysis shows that the stator flux linkage trajectory based on this scheme is consistent with the desired flux linkage trajectory of the control system. The simulation results show that the motor simulation system based on the given flux linkage is reliable and has good control performance, and the effectiveness of the proposed scheme is verified.

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